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Multistage seismic damage constitutive model and parameter calibration of reinforced concrete columns

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Abstract: The road traffic network contains a large number of bridges, and calculating bridge damage using refined models demands significant time and resources. Therefore, developing a rapid evaluation method for the seismic capacity of regular bridges has become a crucial scientific challenge. This study presents an approach in which the ductile column is represented by a single degree-of-freedom model with elastic-plastic constitutive characteristics. Utilizing an uncoupled multivariate power function model and a plastic hinge model, a multidimensional power function model for section hierarchical curvature is constructed. Subsequently, the seismic multistage damage constitutive model (SMSD-CM) of member hierarchy is deduced and calibrated through theoretical methods. This model efficiently derives the trilinear constitutive model of components by inputting several crucial parameters. The SMSD-CM accurately simulates the hysteretic curve and displacement time-history under actual seismic conditions and aligns well with pushover analysis results from tests. The efficiency, ease of operation, and accuracy make the model suitable for rapid evaluation of the seismic capacity of regular bridges within the road traffic network.

Key words: moment-curvature analysis; fragility analysis; curvature ductility; seismic multilevel damage; trilinear model

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The research on urban and rural resilience emphasizes the need to maintain the functionality and recoverability of road traffic networks, especially after earthquakes[1]. With a large number of bridges in these networks, developing rapid evaluation methods for their seismic capacity is crucial.

With the continuous advancement of performance-based seismic design concepts, the multilevel design method has gained widespread acceptance. At present, probabilistic multistage damage models have evolved from two-stage to multistage damage assessments[2]. By dividing the damage process of the structure into stages, namely slight, moderate, severe, and collapsed, these models effectively reflect the behavior of reinforced concrete columns under different load levels. This approach aids engineers in predicting the performance and service life of structures and in formulating appropriate protective measures. For regular bridge columns under linear elastic forces, calculations can be simplified using a single degree of freedom (SDOF) model. However, analyzing inelastic and elastoplastic columns during earthquakes requires establishing complex nonlinear models to accurately assess seismic performance. When conducting nonlinear time-history analyses, the trilinear model is particularly well-suited[3-4], allowing for the formulation of different design goals for various components.

Zhong et al. [5] put forward a parametric analysis approach and an uncoupled multivariate power model (UC-MV-PM) to quickly estimate the curvature ductility of column sections across four damage states by considering four influencing factors. However, exploring the seismic performance of columns only at the section level is insufficient as the seismic deformation capacity of reinforced concrete columns is a crucial research area at the member level. Both actual earthquake damage and indoor model tests show that under axial force and strong seismic activity, the bottom of reinforced concrete columns or the two ends of frame structure columns with large bending moments tend to enter the plastic state first, forming a "plastic hinge"[6]. This means that the stress in that part of the component has reached or exceeded the yield strength of the material, resulting in irreversible plastic deformation. Priestley et al. [7] first proposed a test model for equivalent plastic hinge length, assuming that the column undergoes plastic rotation with the plastic hinge as its core. In this simplified curvature distribution, the yield curvature φ_y is linearly distributed along the pier height H, while the plastic curvature φ_p is uniformly distributed within the "plastic hinge length" L_p.

This hypothetical plastic hinge model emphasizes that

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the equivalent plastic hinge length L_p, as calculated by Priestley et al. [7], includes three deformation components: bending deformation, shear deformation, and steel bar slip of the column. Although the physical concept of the equivalent plastic hinge model proposed by Priestley et al. [7] is not entirely accurate, its simplicity, clarity, and ease of operation have led to its widespread adoption in the elastoplastic analysis of reinforced concrete structures.

Currently, obtaining the hysteretic curve and displacement time history of components mainly depends on experimental methods[8–11]. However, given the significant time and research funds required for large-scale testing, numerical simulation emerges as an important supplementary tool for studying the displacement performance of reinforced concrete bridge piers[12–14]. Commercial software such as OpenSees can generate hysteretic curves and displacement time histories for predefined reinforced concrete piers[15]. Nonetheless, in research requiring extensive data, the substantial modeling workload and the learning cost of the software pose challenges for researchers. Therefore, an accurate and effective pier displacement constitutive model is proposed, which can greatly help researchers study the displacement capacity of piers.

The trilinear model has become a widely adopted method for quickly assessing component performance, with numerous scholars contributing to its research. Yan et al. [16] analyzed the hysteretic curve characteristics of 12 samples of reinforced ultrahigh strength concrete columns and reinforced concrete beam joints under cyclic loading, focusing on damage modes and residual deformations, and proposed a trilinear model for quantifying the hysteretic curve. Ke et al. [17] applied the trilinear model to idealize the hysteretic performance of energy-dissipating damage control building structures, verifying its validity through test results from a typical damage control structure. Using a trilinear moment-curvature response, Yao et al. [18] studied the influence of size on the service life limit of beams with spans ranging from 0.22 to 8.6 m. Ke et al. [19] proposed an empirical trilinear model to quantify the postearthquake residual displacement ratio demands of high-strength steel frames under near-fault seismic ground motions. Godio et al. [20] developed a new trilinear model to describe the force-displacement response of vertical span unreinforced masonry walls under out-of-plane loads. Navas-Sánchez et al. [21] used a simplified trilinear model to explore the characterization of oscillation periods and the kinetic energy of cantilever walls.

Despite the development of threefold constitutive models for different structures and their application in some practical projects, the trilinear constitutive model for reinforced concrete columns remains poorly explored. The existing trilinear constitutive models tend to be very redundant, making them difficult to apply conveniently and quickly, particularly for a large number of bridges within a road traffic network[22].

This article proposes a new multistage seismic damage constitutive and parameter calibration method for reinforced concrete columns. This approach enables designers to better understand the specific applications and differences in strength and ductility indicators of components, facilitating rapid fragility assessment and seismic design for individual bridges and bridge networks. Initially, the ductile pier is modeled as an SDOF system with an elastic-plastic constitutive model. Subsequently, a multidimensional power function model is developed for the hierarchical curvature of the section, and a multilevel seismic damage model of the member is derived and calibrated using theoretical methods. The trilinear model is then compared with commercial software OpenSees and pier experimental data, demonstrating its efficiency, ease of operation, and accuracy.

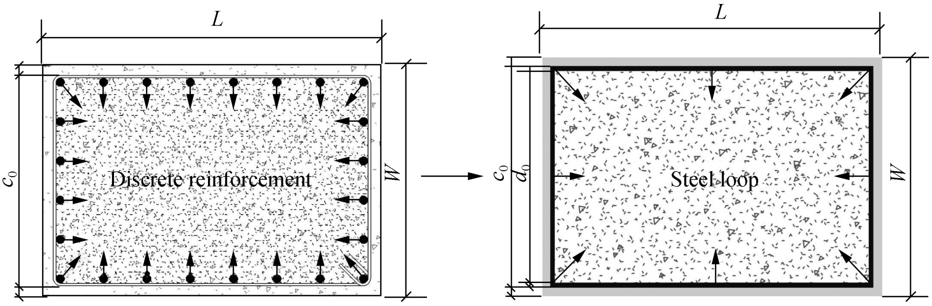
1 Rapid Evaluation of Seismic Performance of Reinforced Concrete Column Section

Evaluating the damage states of a large number of bridges within a road traffic network presents significant challenges in terms of both time and research funding, especially when relying on detailed modeling methods. Therefore, a method that can quickly evaluate the seismic capacity of conventional bridges has a good scientific research prospect.

A parametric moment-curvature approach is proposed for efficiently calculating the section capacity of reinforced concrete bridge columns. This method integrates discrete reinforcement continuous treatment, section dimensionality reduction, and a variable interval integral approach. As shown in Fig. 1, the discrete reinforcement continuous treatment simplifies detailed reinforcement information (such as diameter and spacing) to only the physical information of reinforcement ratio while maintaining accuracy.

The section dimensionality reduction simplifies the section to a one-dimensional model using material thickness information, significantly improving calculation efficiency. The variable interval integral approach uses different curvature increments for different curvature intervals, further boosting calculation efficiency. By inputting the crucial parameters of the section, the moment-curvature curve can be quickly obtained, allowing for determining curvature and curvature ductility based on the defined damage states. Comparisons with experimental data and Xtract demonstrate the excellent accuracy of this method.

Leveraging the high efficiency of the parametric-moment-curvature approach, a sample space of 21^4 limit curvatures, i.e., 194 481 levels, is established. The range of influencing factors within the sample space is shown in Table 1.



Traditional RC section model   Section after reinforcement continuous treatment

Fig. 1 Continuous treatment of discrete longitudinal reinforcement

Table 1 Details of influencing factors

Sectional dimension L			Axial compression ratio R_{ac}			Longitudinal reinforcement ratio ρ_l			Transverse stirrup ratio ρ_s		
Range/m	Increment/m	Levels	Range	Increment	Levels	Range	Increment	Levels	Range	Increment	Levels
[1, 3]	0.1	21	[0.1, 0.3]	0.01	21	[0.01, 0.03]	0.001	21	[0.01, 0.03]	0.001	21

Based on the extensive sample space containing nearly 200 000 limit curvatures, a UCMV-PCM is established. By inputting four crucial parameters of the section, the curvature and curvature ductility for four damage states can be efficiently determined.

$$\begin{aligned}\varphi_y &= 0.005\,4\rho_s^{-0.006\,5}\rho_l^{0.034\,1}R_{ac}^{0.209\,7}L^{-1.016\,0}\\ \varphi_m &= 0.008\,8\rho_s^{-0.010\,0}\rho_l^{0.035\,4}R_{ac}^{0.173\,8}L^{-1.034\,2}\\ \varphi_e &= 0.129\,8\rho_s^{0.847\,4}\rho_l^{-0.246\,4}R_{ac}^{-0.645\,1}L^{-0.987\,6}\\ \varphi_u &= 0.397\,8\rho_s^{0.835\,7}\rho_l^{-0.252\,5}R_{ac}^{-0.623\,8}L^{-0.985\,6}\end{aligned}$$

where ρ_s is the transverse stirrup ratio, ρ_l denotes the longitudinal reinforcement ratio, R_{ac} represents the axial compression ratio, and L indicates the sectional dimension. The model efficiently determines the limit curvature of each damage state by inputting crucial section parameters while also allowing for an intuitive understanding of the capacity of each influencing factor. In the 1st damage state (DS1), the parameters ranked by influence from high to low are L, R_{ac}, ρ_l, and ρ_s. However, in DS3 and DS4, the influence of ρ_s significantly increases, with the order of influence being L, ρ_s, R_{ac}, and ρ_l. L has the strongest influence across all damage states, and R_{ac} is more influential than ρ_l. While ρ_s has little effect in the slight state, its impact surpasses that of R_{ac} and ρ_l in DS3 and DS4.

Although the section-level model offers high efficiency, convenience, and precision, addressing the seismic performance estimation at the column member level remains a crucial challenge in practical engineering.

Based on the established sample space and the UCMV-PCM construction method, a decoupled multivariate power function moment model (UCMV-PMM) for column sections is proposed:

$$\text{DS1:}\quad M_y = 54\,496\rho_s^{0.005\,2}\rho_l^{0.470\,8}R_{ac}^{0.375\,1}L^{3.029\,4}$$

$$\text{DS3:}\quad M_e = 73\,368\rho_s^{0.045\,3}\rho_l^{0.489\,6}R_{ac}^{0.298\,8}L^{3.047\,9}$$

$$\text{DS4:}\quad M_u = 78\,510\rho_s^{0.063\,8}\rho_l^{0.494\,7}R_{ac}^{0.278\,0}L^{3.044\,3}$$

Similarly to UCMV-PCM, UCMV-PMM quickly determines the ultimate bending moment for each damage state by inputting key section parameters, allowing for an intuitive comparison of the influencing capacity of each factor. In each damage state, the parameters ranked from high to low are L, ρ_l, R_{ac}, and ρ_s. There is no doubt that L exhibits the strongest influence across all damage states, aligning with the findings of the UCMV-PCM. ρ_l demonstrates a stronger influence than R_{ac}, which is contrary to the conclusion of the curvature model.

2 Seismic Multistage Damage Constitutive Model (SMSD-CM)

Based on the hypothetical model of equivalent plastic hinges, the influences of reinforcement slip and shear effect are considered. To accurately calculate the column top displacement, it is necessary to determine the length of the plastic hinge of the column under actual stress conditions. The plastic hinge formula proposed by Berry integrating a large number of column experimental data in the PEER database is the following:

$$L_p = 0.05H + 0.1\frac{f_y d_b}{\sqrt{f'_c}} \tag{1}$$

where d_b is the diameter of longitudinal reinforcement, f_y denotes the yield strength of longitudinal reinforcement, f'_c represents the compressive strength of core concrete, and H indicates the clear height of the column.

Utilizing the UCMV-PCM and UCMV-PMM, critical section parameters can be input to efficiently derive the limit curvature and moment for each damaged state of the column. By applying the equivalent plastic hinge model proposed by Priestley et al. [7], combined with Berry's plastic hinge formula and the limit curvature for each state, the plastic hinge length and top displacement for each damage state are determined. Additionally, using the overall moment balance of column members, the shear force at the column bottom, accounting for the P-Δ effect, is calculated. The specific solution process and corresponding equations of the key point coordinates of the trilinear constitutive model are as follows:

$$\Delta_y = \frac{\varphi_y H^2}{3} \tag{2}$$

$$\Delta_e = \Delta_y + (\varphi_e - \varphi_y) L_p \left(H - \frac{L_p}{2}\right) \tag{3}$$

$$\Delta_u = \frac{\varphi_y H^3}{3} + (\varphi_u - \varphi_y) L_p \left(H - \frac{L_p}{2}\right) \tag{4}$$

where $P = R_{ac} f_{co} LW$ is the axial load on the column, and H denotes the clear height of the column,

$$F_y = (M_y - R_{ac} f_{co} LW\Delta_y)/H \tag{5}$$

$$F_e = (M_e - R_{ac} f_{co} LW\Delta_e)/H \tag{6}$$

$$F_u = (M_u - R_{ac} f_{co} LW\Delta_u)/H \tag{7}$$

where M is the moment of the column bottom, and Δ denotes the total top displacement of the column.

The force-displacement trilinear constitutive model of column is obtained by connecting the key points of column top displacement and column bottom shear force across each damage state, as shown in Fig. 2.

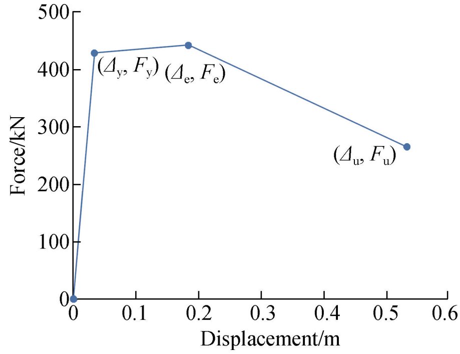


Fig. 2 Trilinear model for seismic assessment of the column

2.1 Effects of the crucial parameters on SMSD-CM

Based on the constructed SMSD-CM, the influence of crucial parameters on column bottom shear force and top displacement is analyzed, focusing on the mechanisms and influence capacity of different parameters such as L, R_{ac}, ρ_1, and ρ_s. By keeping the crucial parameters invariant and varying the target parameters under study, their effects on damage displacement or force are observed, as shown in Fig. 3. The range of values and constant value for each parameter are recorded in Table 2.

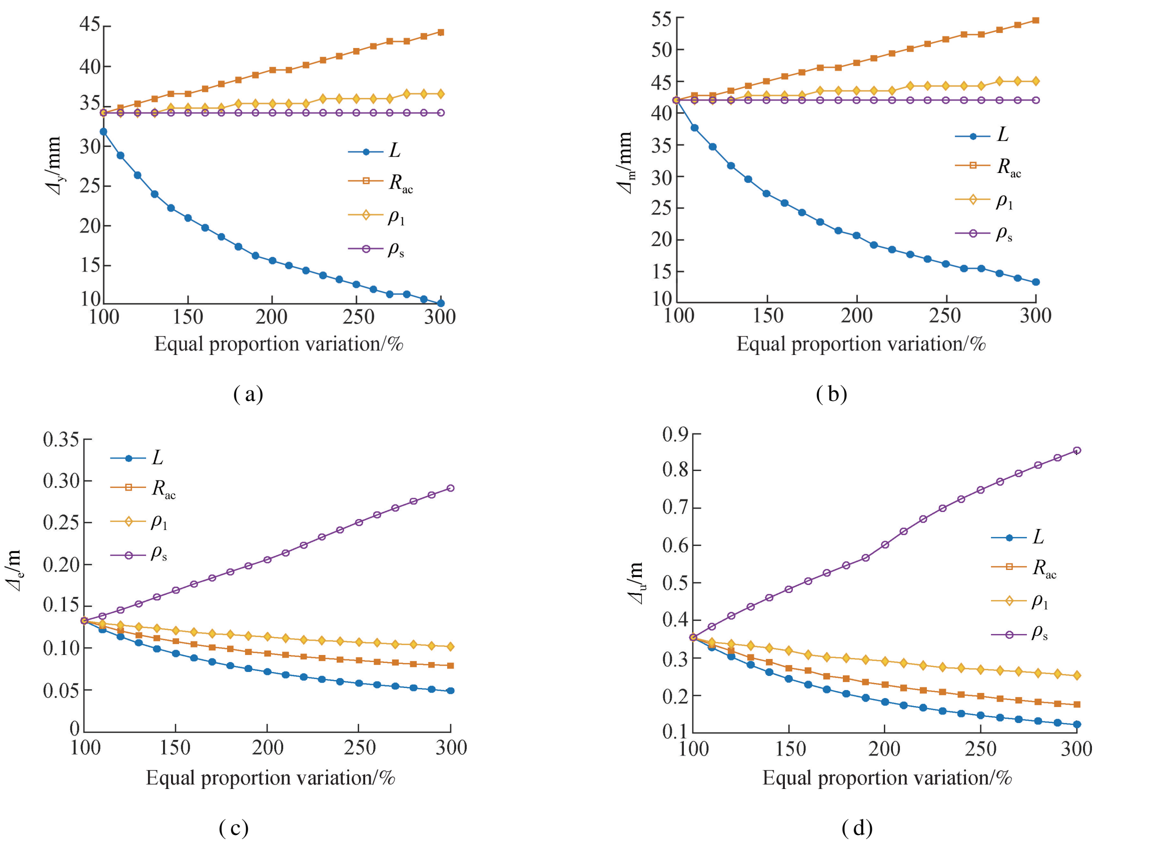


Fig. 3 Influence of crucial factors on column displacement across different damage states. (a) Slight damage; (b) Moderate damage; (c) Severe damage; (d) Collapse

Table 2 The range of values and constant value for crucial parameters

Parameter	Lower value	Upper value	Constant value
Sectional dimension L/m	1	3	1
Axial compression ratio R_{ac}	0.1	0.3	0.1
Longitudinal reinforcement ratio ρ_l	0.01	0.03	0.012
Transverse stirrup ratio ρ_s	0.01	0.03	0.012 2

Fig. 3 illustrates that in DS1 and DS2, displacement is most significantly influenced by L, with both Δ_y and Δ_m decreasing significantly as L increases. Δ_y and Δ_m increase with rising R_{ac} and ρ_l, with R_{ac} having a more obvious impact than ρ_l, while the influence of ρ_s is negligible. In DS3 and DS4, the influence ability of crucial parameters from high to low is ρ_s, L, R_{ac}, and ρ_l. It is worth noting that the influence capacity of ρ_l is small but cannot be neglected. Δ_e and Δ_u are most responsive to changes in ρ_s, with an obvious increase in displacement as ρ_s rises in DS3 and DS4. The influence mechanism aligns with the conclusion of UCMV-PCM, pointing out that enhancing the structure's displacement ductility can be achieved by increasing ρ_s without changing the member's Δ_y.

Fig. 4 shows that with proportional changes in crucial parameters, the column bottom shear force in each damage state is most obviously affected by L, and its influence capacity increases as L grows. In DS1, DS2, and DS3, the descending order of influence for each factor is L, ρ_l, R_{ac}, and ρ_s, aligning with the conclusions of UC-MV-MMP. In DS4, owing to the significant influence of ρ_s on Δ_u, ρ_s exceeds R_{ac} in its influence on F_u. While ρ_s has little effect on F_y and F_m in DS1 and DS2, it causes a decrease in F_e and F_u as ρ_s increases in DS3 and DS4.

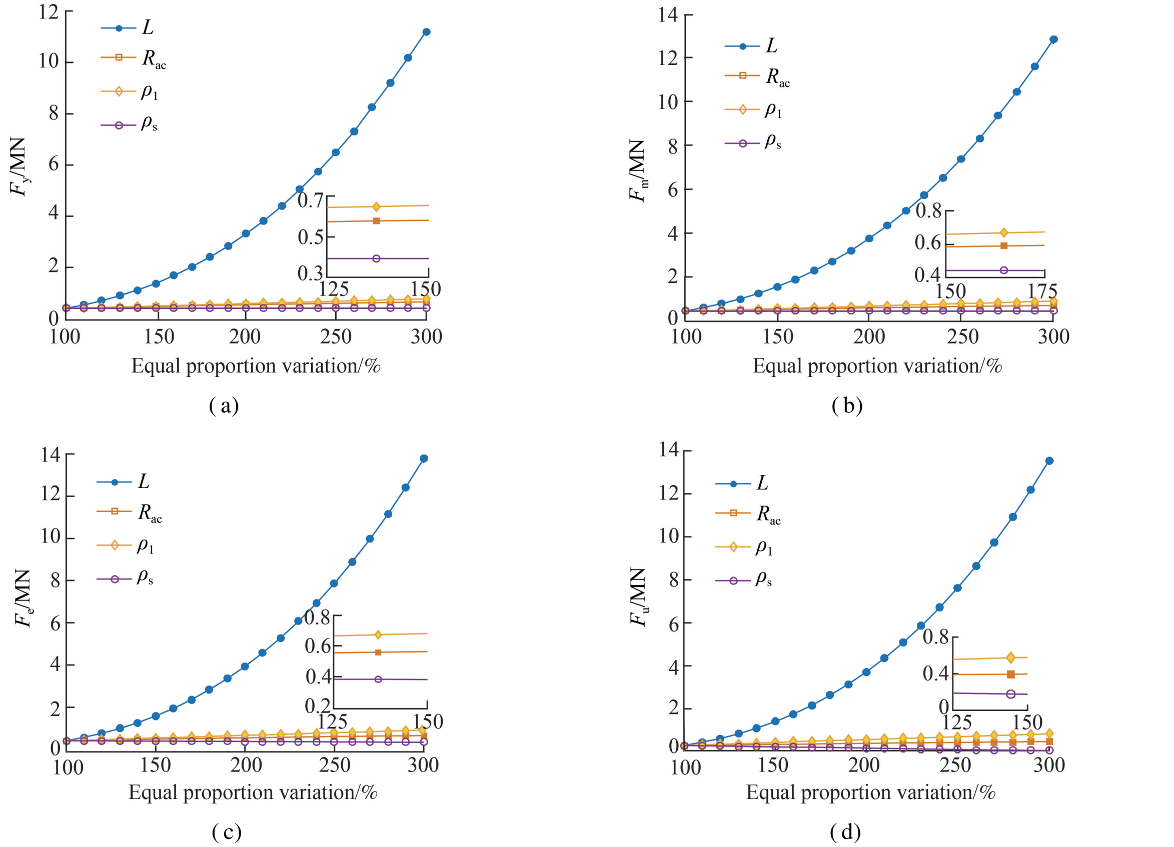


Fig. 4 Influence of crucial factors on the column force across different damage states. (a) Slight damage; (b) Moderate damage; (c) Severe damage; (d) Collapse

2.2 Verification of pushover and hysteretic curve

To verify the applicability and accuracy of SMSD-CM in practical engineering, a fiber model was established on the OpenSees platform and compared with the SMSD-CM. OpenSees is a comprehensive and continuously developing open software system for seismic response simulation in structural and geotechnical aspects, developed mainly by the University of California, Berkeley. The column has a clear length of 6 m and a section dimension L of 2 m, as shown in Fig. 5. C50 concrete was used for confined and unconfined applications, with an f_{co} of 32.4 MPa, while Concrete04 in OpenSees was employed to simulate the material properties of concrete. For the longitudinal rebar, HRB400 was used, with f_y being 360 MPa and ρ_l being 0.012. Steel01 in OpenSees simulated the material properties of steel. The section was designed with a R_{ac} of 0.1. HRB400 was used for the stirrup, with

f_{yh} being 360 MPa and ρ_s being 0.012 2.

By inputting the crucial parameters of the column, the SMSD-CM was obtained and compared with the pushover results using the traditional isolated column model established in OpenSees. The verification results are shown in Fig. 6.

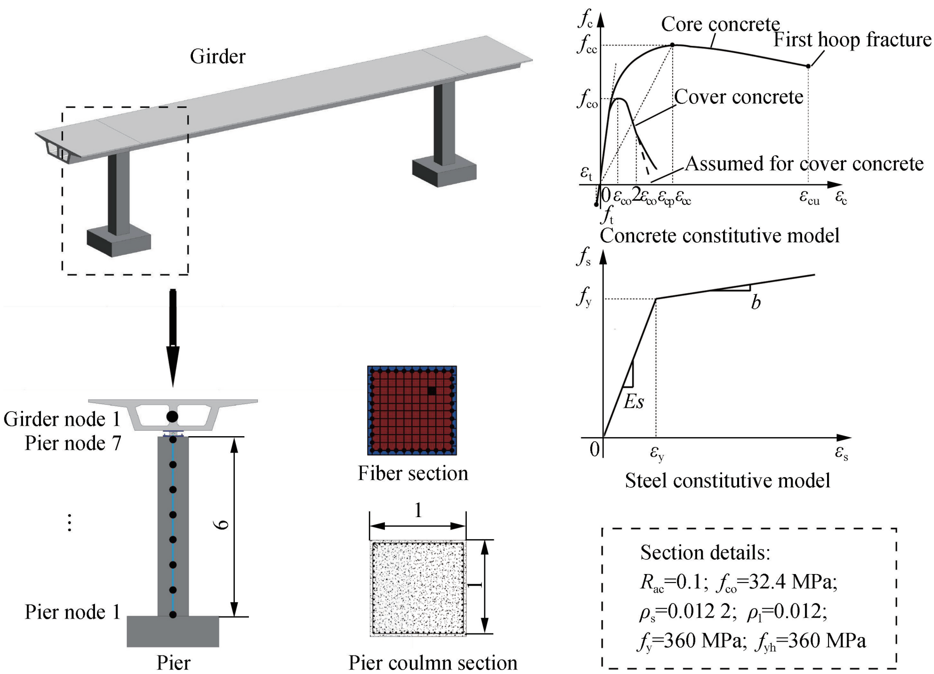


Fig. 5 Construction information of OpenSees model (unit: m)

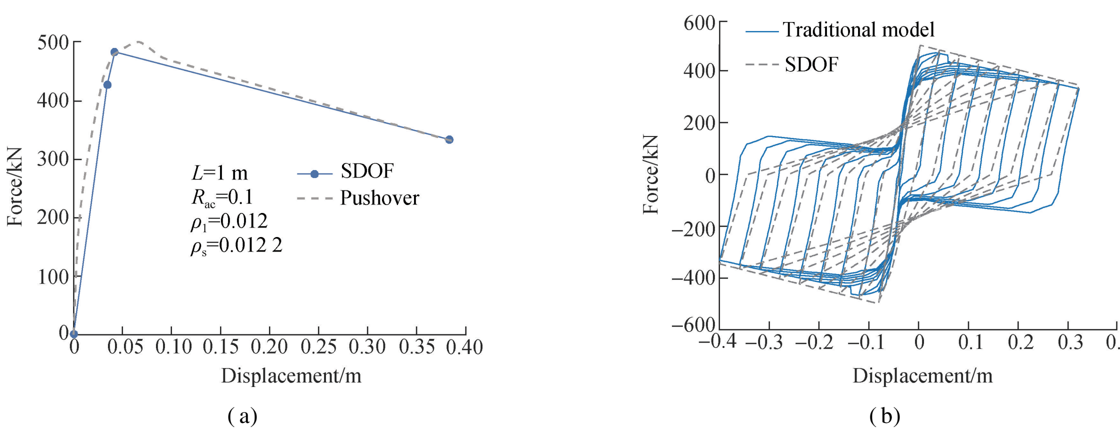


Fig. 6 Comparison results between trilinear models and OpenSees. (a) Trilinear models; (b) Hysteretic curves

The observation shows that the key points of the SDOF model align well with the pushover results of the traditional column model in DS1, and in DS3 and DS4, they almost coincide, demonstrating the SDOF's effective fitting effects. Further analysis is needed to examine the influence of changes in crucial parameters on damage displacement and force and to understand how various factors affect the fitting effect of the SDOF.

Figs. 7 (a) and (b) reveals that the pushover and hysteretic curve of SDOF maintain good fitting accuracy as L changes. An increase in L leads to a significant decrease in ultimate displacement, while the column's peak force increases significantly. Figs. 7 (c) and (d) shows that the ultimate displacement decreases with increasing R_{ac}, while the column's peak force grows. The fitting accuracy of SDOF's pushover and hysteretic curve decreases to a certain extent with variations in R_{ac}. Figs. 7 (e) and (f) illustrates that as ρ_l increases, the ultimate displacement across all damage states remains relatively stable, but the column's peak force increases significantly. Figs. 7 (g) and (h) demonstrates that with an increase in ρ_s, ultimate displacement across damage states increases obviously, while the peak force of the column hardly changes. SDOF exhibits excellent fitting performance under varying ρ_l and ρ_s.

The accuracy of SDOF in quasi-static analysis is verified by comparing its pushover curve and hysteretic curve with that of a traditional column model. Using the plastic hinge model and combined with UCMV-PCM and UCMV-PMM, we propose SMSD-CM. This model effectively quantifies the seismic performance of columns,

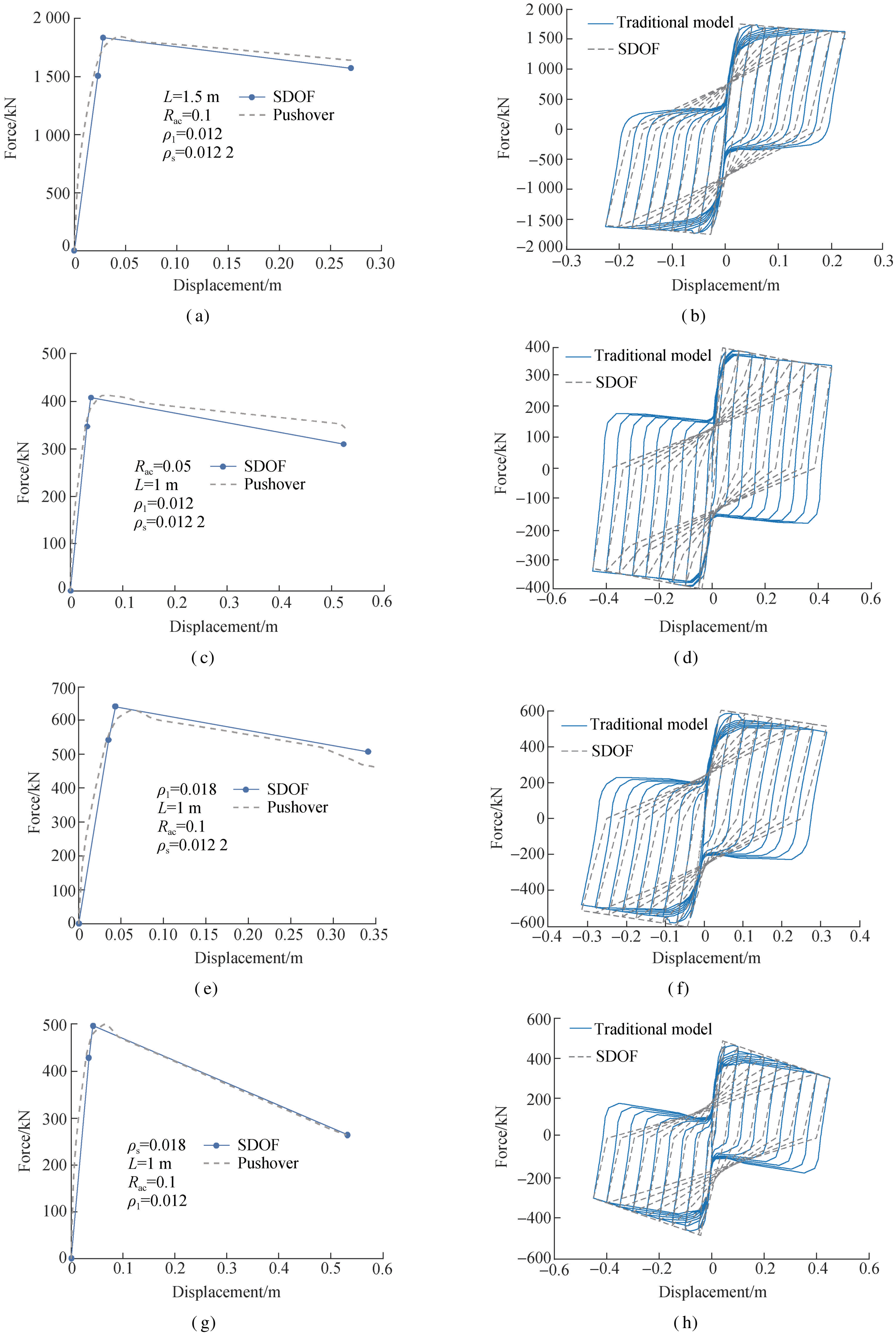


Fig. 7 Verification of the influence of crucial parameters. (a) Trilinear models with different sectional dimensions; (b) Hysteretic curves with different sectional dimensions; (c) Trilinear models with different axial compression ratios; (d) Hysteretic curves with different axial compression ratios; (e) Trilinear models with different longitudinal reinforcement ratios; (f) Hysteretic curves with different longitudinal reinforcement ratios; (g) Trilinear models with different transverse stirrup ratios; (h) Hysteretic curves with different transverse stirrup ratios

demonstrating excellent fitting performance. It can be used to quickly determine the stress displacement curves for column damage states, thus facilitating research in nonlinear time-history analysis and pushover analysis of columns.

2.3 Comparison and verification between SMSD-CM and experimental data

This section compares the predicted results of SMSD-CM with experimental data. The PEER database, which contains a large number of column experimental data, provides detailed parameters for each column. From this database, specific column members are selected to be compared with the SDOF proposed in this study. The details of these columns are shown in Table 3.

Table 3 Crucial information regarding column specimens

Specimen No.	f_{co}/MPa	f_{yh}/MPa	f_y/MPa	L/mm	W/mm	H/mm	ρ_l/%	ρ_s/%	R_{ac}
1[23]	32.0	325	511	550	550	1 650	1.25	1.7	0.1
2[23]	32.1	325	511	550	550	1 650	1.25	2.1	0.3
3[23]	26.9	305	432	400	600	1 784	1.88	2.2	0.1
4[24]	27.2	428	448	380	610	2 335	2.22	0.4	0.098
5[24]	27.2	428	448	380	610	2 335	2.22	0.4	0.239
6[24]	28.1	428	448	380	610	2 335	2.22	0.5	0.232

To determine the bending moment and curvature of a reinforced concrete member's section, it is essential to input its key parameters and use the parametric section moment-curvature method. By integrating this with the plastic hinge model, it is possible to calculate the column's top displacement of the column and base shear, accounting for the P-Δ effect. This process results in the SMSD-CM for each experimental member. The pushover analysis results of the trilinear model are compared with the experimental hysteretic curve, as shown in Fig. 8.

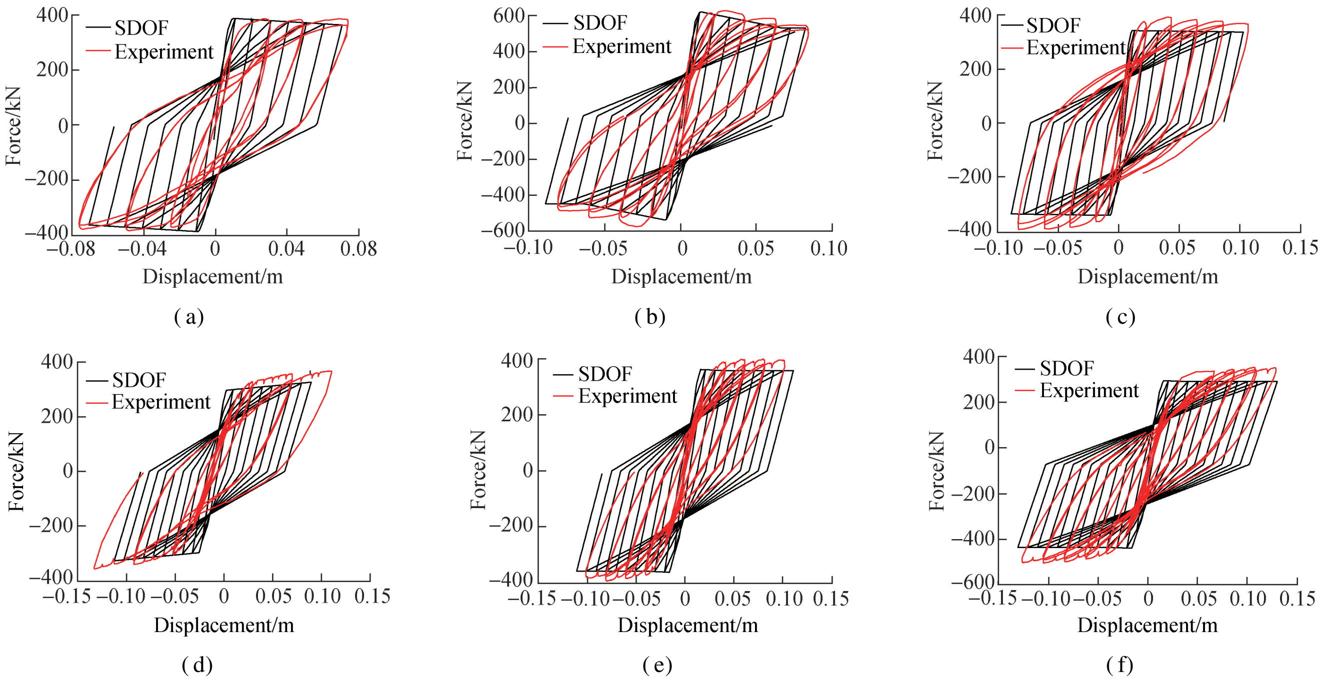


Fig. 8 Trilinear model and experimental hysteretic curve. (a) Specimen 1; (b) Specimen 2; (c) Specimen 3; (d) Specimen 4; (e) Specimen 5; (f) Specimen 6

Fig. 8 demonstrates that the hysteretic curve obtained by SMSD-CM closely aligns with the experimental data, especially in terms of peak displacement and peak lateral force. The SMSD-CM model not only accurately simulates the hysteretic curve and displacement time-history under actual seismic conditions but also validates its practical engineering application through comparison with test data. The proposed model is efficient, user-friendly, and accurate, making it suitable for further academic research.

3 Conclusions

In previous studies, researchers often relied on empirical damage state thresholds derived from experimental data. However, using different damage thresholds for the same type or even group of specimens can lead to different, sometimes significantly different, research results, complicating the comparison of seismic performance across similar bridge piers. In addition, large-scale experimental projects require massive time and funding, and the process of modeling each one individually using commercial software modeling can be challenging for researchers needing a large amount of research data. This study proposed a novel multilevel damage model of reinforced concrete columns designed to quickly evaluate the seismic performance of massive regular bridges in road bridge networks. This advancement is crucial for ensuring the seismic safety of bridge engineering and the smooth traffic lifeline. Future research will explore the organic integration of multilevel seismic damage constitutive models into fragility analysis and expand the model's applicability to components with different material properties and cross-sectional types. The main conclusions of this paper are summarized as follows:

1) For DS1 and DS2, L has the most significant influence on the displacement. The influence of R_{ac} is more obvious than that of ρ_l, while the influence of ρ_s is negligible. Δ_y and Δ_m decrease significantly as L increases, but they increase as R_{ac} and ρ_l increase. In DS3 and DS4, the crucial parameters ranked by influence from high to low are ρ_s, L, R_{ac}, and ρ_l. Although ρ_l has a small impact, it cannot be neglected.

2) The column bottom shear force in each damage state is most obviously affected by L, and this influence grows as L increases. In DS1, DS2, and DS3, the influence ability of each factor in descending order is L, ρ_l, R_{ac}, and ρ_s, aligning with the findings of the UCMV-MMP study. In DS4, owing to the significant influence of ρ_s on Δ_u, the influence of ρ_s on F_u exceeds that of R_{ac}. The ρ_s has little effect on F_y and F_m in DS1 and DS2, while F_e and F_u decrease as ρ_s increases in DS3 and DS4.

3) The model efficiently calculates the SMSD-CM of reinforced concrete members by inputting several crucial parameters. The SMSD-CM accurately simulates the hysteretic curve and displacement time history under actual seismic conditions and aligns well with pushover analysis test results, demonstrating its efficiency, ease of use, and accuracy.

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钢筋混凝土柱多级地震损伤本构模型及参数标定

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摘要:道路交通网络中存在大量桥梁,而基于精细模型的桥梁损伤计算对时间和资金要求很高,因此研究常规桥梁抗震能力的快速评估方法已成为亟待解决的关键科学问题之一.将延性柱等效为具有弹塑性本构的单自由度模型.基于非耦合多变量幂函数模型（UCMV-PM）和塑性铰模型,建立了截面分级曲率的多维幂函数模型,然后通过理论方法推导和校准了构件分层的地震多阶段损伤本构模型（SMSD-CM）.该模型通过输入几个关键参数,可以有效地获得构件的三折线本构模型.SMSD-CM 不仅可以准确地模拟实际地震波下的滞回曲线和位移时程,而且与试验的推覆分析结果高度一致,证明该模型高效、准确且易于操作,可用于快速评估道路交通网络中常规桥梁的抗震能力.

关键词:弯矩曲率分析;易损性分析;曲率延性;地震多级破坏;三折线模型

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